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ABATEMENT OF PARTICULATE EMISSIONS FROM STATIONARY SOURCES

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A program of government and industry research for dealing with particulate emissions is outlined in this report. This program is based on an evaluation of current technology and an assessment of what developments in control and measurement techniques can reasonably be expected during the next five to ten years. The report identifies and summarizes technical problems in the first chapter in which a six-point program for improving particulate-emission control is proposed. The background and scope of the study are discussed in the second chapter while emission sources and particle collection technology are reviewed in the third and fourth chapters. The two remaining include discussions of the measuring and monitoring of particle concentrations and of the characteristics of fine particles.

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ABATEMENT OF PARTICULATE EMISSIONS FROM STATIONARY SOURCES

Prepared by
Ad Hoc Panel on Abatement of Particulate
Emissions from Stationary Sources
Committee on Air Quality Management
Committees on Pollution Abatement and Control
Division of Engineering
National Research Council
National Academy of Engineering

Washington, D.C.
1972

This is the report of a study undertaken by the Committee on Air Quality Management *Ad Hoc* Panel on Abatement of Particulate Emissions from Stationary Sources for the National Academy of Engineering in execution of work under Contract No. CPA 70-48 with the Office of Air Programs of the Environmental Protection Agency

As a part of the Division of Engineering of the National Research Council, National Academy of Engineering, the Committees on Pollution Abatement and Control perform study, evaluation, or advisory functions through groups composed of individuals selected from academic, governmental, industrial, and public sources for their competence and interest in the subject under consideration. Members of these groups serve as individuals contributing their personal knowledge and judgment and not as representatives of any organization in which they are employed or with which they may be associated.

PREFACE

In this report, a program of government and industry research for dealing with particulate emissions from stationary sources is outlined. It is based on an evaluation of current technology and an assessment of what developments in control and measurement techniques can reasonably be expected during the next five to ten years.

The effects of particulate emissions on human beings and the environment are complex. Detailed consideration of these effects is beyond the scope of this report but, along certain broad lines, they have been taken into account in the Panel's discussion.

It is important to understand that each increment in control of air pollution requires a shift in our national resources and capital investment and that such shifts are almost certain to lead to increased costs for energy and materials. The challenge is to minimize such increases while accomplishing our goals by properly designing industrial processes and systems for pollution abatement and control.

The Panel's evaluation of the current status of and trends in particulate-emission-control technology and its recommendations for improving and maintaining the quality of our atmosphere have been based on presentations by manufacturers of gas-cleaning devices and the Office of Air Programs, several comprehensive reviews prepared by industrial organizations and research institutes, and the review of many reports and technical documents, in addition to the general knowledge of the field possessed by the Panel, Committee, and Academy review groups. The Panel is particularly grateful to Mr. Robert C. Lorentz, Division of Control Systems, Office of Air Programs, Environmental Protection Agency, and his staff for their valuable support.

Technical problems are identified in this report, the solution of which will require the initiation of significant new engineering and scientific

research programs. These problems are summarized in the first chapter in which a six-point program for improving particulate-emission control is proposed. The background and scope of the study are discussed in the second chapter, while emission sources and particle-collection technology are reviewed in the third and fourth chapters, respectively. Since the measuring and monitoring of particle concentrations is an important and difficult task, a separate chapter on this subject has been included. Finally, the characteristics of fine particles, which have been identified as a major problem area, are discussed in the sixth chapter.

Despite the institution of new emission-control measures, particulate levels remain high in many of our cities. The programs proposed here can substantially improve and maintain the quality of our air environment. The need for such programs is now recognized by a concerned citizenry.

S. K. Friedlander
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I

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. SUMMARY

Particulate emissions are readily visible when in high concentration and, for this reason, were the first form of air pollution to be controlled. In recent years, gaseous pollutants have received the major attention, but continuing deterioration of visibility in our urban areas, together with the possibility of unfavorable climatic and health effects, has led to renewed concern for controlling particles in the atmosphere.

The Panel finds that existing technology for particle collection is adequate for the removal of the major fraction of the mass of particulate matter currently being emitted to the atmosphere from confined sources, but reducing the total mass of such emissions is only a first step.

Particles in effluent gases are distributed over a wide range of sizes from a few angstroms to several microns in diameter. Since collection is less efficient for small than for large particles, significant numbers of particles less than 2 microns in diameter escape into the atmosphere. These small particles, equivalent in mass to a considerably smaller number of large particles, have a much greater impact on visibility, health, and water-droplet nucleation than do the larger particles. *Therefore, tonnage-collection figures and weight-removal efficiencies are inadequate to delineate the entire particle-emission problem.*

Thus, the Panel finds that *small particles, together with particulate matter formed in the atmosphere from gas-phase reactions and condensation, may continue to limit visibility and may affect health even when presently uncontrolled sources of particulate matter are equipped with the best collection devices available.*

B. CONCLUSIONS

On the basis of its review of particulate-emission-control technology, the Panel draws the following conclusions:

1. *At the 1970 level of control it is estimated that particulate emissions from industrial sources will increase from the present estimated level of 18 million tons per year to over 50 million tons per year by the year 2000.*

2. Existing methods for the removal of particulate matter from gases are adequate for control of the greatest part, by weight, of the emissions from stationary sources. On a total mass basis, the average efficiency that can be achieved with many types of particle-control equipment now being installed is well over 90 percent for most industrial applications and may exceed 99 percent.

3. Four major categories of industrial particle-control equipment (electrostatic precipitators, fabric filters, scrubbers, and inertial or centrifugal mechanical collectors), each having special characteristics that determine its suitability for a particular gas-cleaning application, have been available for many years, but they are not universally applied to all sources in all industries. For example, it is estimated that 38 percent of stoker-fired industrial boilers and 75 percent of crushed-stone operations are not controlled, thus leading to the release of 2 million tons of coal fly ash and 4.5 million tons of rock dust per year--almost 40 percent of the estimated mass of particulate emissions from all major industrial sources.

4. *The application of the best existing technology to presently uncontrolled and inadequately controlled stationary industrial sources will permit major reductions in the total weight of particulate matter emitted to the atmosphere.* Depending upon the level of control required, such applications may be accompanied by significant increases in production costs.

5. *It may not be sufficient to evaluate the performance of pollution-control equipment on the basis of mass emissions alone.* Particle size, composition, and the presence of co-contaminants must also be taken into account; special emphasis needs to be placed on the amount of material in the fine-particle size range and on its chemical nature.

6. Portions of certain polluting gases are converted to aerosols in the atmosphere and contribute significantly to the local and national burden of suspended particles. However, this formation of fine particles by secondary processes is not well understood. *The relative importance of secondary-particle formation must be taken into account when setting standards. Otherwise, reduction in particulate emissions may not lead to the expected improvement in air quality.*

7. Presently available control equipment has achieved only limited effectiveness in that: its collection efficiency for fine particles may not be adequate; and it is not generally applicable to situations where co-contaminants must be dealt with because of the characteristics of the materials. *Significant increases in efficiency over certain size ranges, particularly the fine-particle, as well as much needed improvements in reliability,*

may be achieved by intensifying engineering research and development in the particle-control field.

8. *In general, the ranges of operation of the various collection devices with respect to temperature, humidity, and corrosiveness of the gases should be significantly extended.* Other current needs include better fabric-filter cleaning techniques, improved filter fabrics for longer life and better performance, more reliable electrostatic precipitator components, better designs to increase the charging-wire life, and more efficient and reliable equipment.

9. *Major gaps exist in instrumentation for sampling and measuring the characteristics of particulate pollution.* These gaps have hampered the development of rational emission and ambient-air-quality standards. The state of technological and scientific knowledge is sufficiently advanced, however, to support significant improvements, especially in aerosol instrumentation.

C. RECOMMENDATIONS

There is a great need for Environmental Protection Agency leadership in planning and coordinating a national program to ensure that the needs identified in this report are met in a reasonable and timely manner. To meet this need, the Panel recommends that:

1. *Collaborative federal programs be developed with gas-cleaning equipment manufacturers and users to gather basic engineering performance data on particle-collection equipment* as a function of particle size; special emphasis should be placed on measuring collection efficiencies in the fine-particle range.

2. *The Environmental Protection Agency support an expanded and coordinated experimental program designed to gather information on the size distribution, especially in the fine-particle range, and on the chemical composition of particles and carrier gas emitted from stationary sources.*

3. *Engineering research and development on particle-control technology be intensified and special emphasis be placed on the 0.2- to 2.0-micron diameter range.* This could involve a cooperative effort jointly funded by the Environmental Protection Agency, manufacturers of industrial gas-cleaning equipment, and major equipment users, thus obtaining better control without creating an intolerable individual plant or industry-wide economic burden and impairing international competitive positions.

4. *Support be given a major research program to improve existing in-stack sampling systems and to develop new stack monitoring systems for measuring the physical and chemical characteristics of particulate emissions.* A sizable research investment must be made, and it is particularly important that efforts continue on the development of parallel systems for ambient-air measurement.

5. *Improved methods be developed to relate the characteristics of emission sources to atmospheric particulate pollution.* This will require an expansion of research on the origin and behavior of fine particles and their interaction with reactive gases.

6. *Emission standards and ambient-air-quality standards be reviewed to more strongly take into account hazardous particles.*

Criteria and standards for agents such as lead, asbestos, and carcinogens, associated with particulate matter, should be related to particle-size and other aerosol characteristics.

The level of support by the Environmental Protection Agency for research and development on the abatement of particulate emissions is approximately $500,000 in fiscal year 1972. The Panel believes that this level of support, together with industrial expenditures, is grossly inadequate for the program needs outlined above. A considered estimate of the cost of such a program indicates that in excess of $5 million per year over the next 10 years should be spent by the Environmental Protection Agency on research and development.

II

INTRODUCTION

A. THE CLEAN AIR AMENDMENTS OF 1970

The increasing concern of Americans for the present and future state of the nation's air resources is reflected in the Air Quality Act of 1967[1] (Public Law 90-148 as amended) and the Clean Air Amendments of 1970[2] (Public Law 91-604 in which P.L. 90-148 was further amended to provide for a more effective program to improve the quality of the nation's air). These Acts provide for emissions standards for existing sources, which are to be established and enforced by the states, and efficiency standards for new sources, some of which were promulgated during 1971 by the Environmental Protection Agency (EPA).[3] All standards are subject to review and revision. Responsibility at the federal level for carrying out the provisions of these laws remains with the EPA Administrator.

On April 30, 1971, the EPA published in the *Federal Register* the *National Primary and Secondary Ambient Air Quality Standards*[4] which were set by the Administrator. These standards are based on air-quality-criteria documents[8-16] published by the EPA and allow an adequate margin of safety to protect the public health (primary standards) and the public welfare (secondary standards) from all known or anticipated adverse effects associated with the presence of pollutants in the ambient air:

The national primary ambient-air-quality standards for particulate matter are:

(a) 75 micrograms per cubic meter--annual geometric mean.

(b) 260 micrograms per cubic meter--maximum 24-hour concentration not to be exceeded more than once per year.

The national secondary ambient-air-quality standards for particulate matter are:

(a) 60 micrograms per cubic meter--annual geometric mean, as a guide to be used in assessing implementation plans to achieve a 24-hour concentration.

(b) 150 micrograms per cubic meter--maximum 24-hour concentration not to be exceeded more than once per year.

Under the provisions of these laws, the EPA published in August 1971 in the *Federal Register*, guidelines to the states[5] for preparation, adoption, and submittal of implementation plans for enforcement of national ambient-air-quality standards.

Under Section 110,[2] the states were given until February 1972 to submit a plan providing for implementation, maintenance, and enforcement of the primary standards in each air-quality-control region and an additional nine months to submit a similar plan for secondary standards. These plans are to include a timetable for compliance with primary standards within three years and with secondary standards within a reasonable time. States may adopt standards more stringent than the federal standards.

The EPA recommendations[5] to the states for their implementation plans cover maximum emissions of particles and gases. These, together with recently promulgated federal standards of performance for certain new stationary sources, are as follows for particulate matter:

	Required for New Sources*	Recommended for Existing Sources
Fuel-Burning Equipment	0.10 lb per million Btu, 20% opacity	0.30 lb per million Btu

*Mass emission limitations provide control for all particles. Opacity restrictions limit emission of fine particles that have high light-scattering capability per unit mass.

	Required for New Sources	Recommended for Existing Sources
Incinerators	0.08 gr/scf corrected to 12% CO_2	0.20 lb per 100 lb charged
Portland Cement Plants	Kiln: 0.30 lb per ton of feed, 10% opacity Clinker Cooler: 0.10 lb per ton of feed, 10% opacity	Use of process weight formula, ranges between 1.0 and 0.1 lb per ton of feed
Sulfuric Acid Plants	0.15 lb of mist per ton of acid produced, 10% opacity	----------

B. ROLE OF THE ACADEMIES

In 1967 the National Academy of Sciences and the National Academy of Engineering established the Environmental Studies Board to coordinate activities of the two Academies in the environmental field. One of the first acts of this Board was to recommend the establishment within the Division of Engineering, National Research Council, of four committees on air, water, noise, and solid-waste management. These committees have an engineering orientation and are available to offer advice and assistance to the Congress and to agencies of the executive branch of government having responsibility for pollution abatement and control.

In June 1969, the National Air Pollution Control Administration (NAPCA) of the U.S. Department of Health, Education, and Welfare (now the Office of Air Programs of the Environmental Protection Agency) requested the National Academy of Engineering to make a comprehensive review of present industry and government research, development, and demonstration programs and

to include an examination of technical and economic potentials, adequacy of scope, proper integration with similar efforts, and responsiveness to national needs directed toward control of sulfur oxides effluents from stationary sources of combustion. The report of that review, *Abatement of Sulfur Oxide Emissions from Stationary Combustion Sources,*[17] was published in May 1970.

The newly formed Office of Air Programs (OAP) of the EPA then requested the National Academy of Engineering-National Research Council to provide additional studies of sulfur oxides emissions from industrial sources, nitrogen oxides emissions from stationary sources, and particulate emissions from stationary sources. In this report on particulate emissions from stationary sources, the Panel was asked to review the status of particulate emissions and control technology and to recommend research, development, and demonstration programs to meet the national need for control of emissions, including fine particles, from stationary sources.

C. SCOPE OF THE PARTICULATE-POLLUTION PROBLEM

Atmospheric particulate matter is produced from natural sources such as the sea and the soil and from man-made sources such as fuel combustion in power plants, various industrial processes and internal-combustion engines. Atmospheric particulate matter can be classified as primary--introduced into the atmosphere in particulate form, or secondary--formed in the atmosphere from certain gases by chemical and physical processes.

The particulate-pollution problem is only partly a primary-particle-emission problem. For example, as shown in Table 1, in Los Angeles about 35 percent of the particulate matter is formed in the atmosphere in a secondary fashion from gaseous pollutants; an additional 15 to 20 percent is derived from natural sources. The motor vehicles in Los Angeles are responsible for approximately 15 percent of the primary-particulate-matter emissions. Los Angeles is especially subject to photochemical smog formation and cannot be

TABLE 1

ESTIMATED CONCENTRATIONS OF LOS ANGELES AEROSOL PARTICLES BY SOURCE[18]
(annual average)

Source		Mass Concentration ($\mu g/m^3$)
Natural Background		
Primary		14-26
Dust rise by wind	8-20	
Sea salt $\{^{Na^+}_{Cl^-}$	3 3	
Spores, pollen, etc.	Unknown	
Secondary		4-7
Vegetation (organic vapors)	3-6	
Biological (soil bacterial action, decay of organics)-NH_3, NO_x, S...	0.7	
Man-Made		
Primary		36
Motor vehicles	15	
Organic solvent usage	6	
Petroleum	1.3	
Aircraft	4	
Combustion of fuels	5	
Other	5	
Secondary		39
Reactive hydrocarbon vapors	11	
NO_3^-	13.5	
$SO_4^=$	14.4	
TOTAL ACCOUNTED FOR / MEASURED TOTAL		93-108 / 119

considered typical of the areas where coal and fuel-oil combustion products represent the major emissions (i.e., the industrial centers of the East and Midwest).

Secondary conversion processes and sedimentation make it difficult to relate atmospheric particulate pollution levels to the characteristics of pollution sources, even when the turbulent dispersion patterns are known. This difficulty has hampered the development of effective control strategies and the establishment of meaningful emission standards. *Currently, methods are being developed to relate air quality to emission sources, both gaseous and particulate. High priority should be given to such studies for urban and industrial regions with differing source characteristics.*

During fiscal year 1970, the EPA budget for measurement and control of particulate emissions from stationary sources was about $1 million; it decreased to $640,000 in fiscal year 1971 and is $500,000 in fiscal year 1972. This effort includes development of measurement methods, emissions inventory, and improved control equipment and systems for all applications. This level of funding is grossly inadequate. Beginning a balanced federal program to improve particulate-control capability of the type described in the *Recommendations* will require expenditures at least 10 times greater. Substantial increases in both federal and industrial support are required to make progress toward the level of control commensurate with the national need.

D. IMPORTANCE OF PARTICLE SIZE AND CHEMICAL COMPOSITION

A difficulty arises in assessing the importance of particulate emissions because the particles cover a wide size range. Most of the data on emissions and collection-equipment efficiency are reported on a gross-weight-collected basis. It is, therefore, not possible to distinguish between the emission of a few large particles or of many smaller particles[14,15] of equal weight, whereas the difference between equal weights of small and large particles released to the atmosphere is very great with respect to atmospheric residence time, visibility, lung deposition, cloud nucleation, and weather modification.

Another important factor is the chemical nature of the particles as it relates to toxicity, e.g., power-plant fly ash produced by the combustion of pulverized coal consists of a diverse mixture of metal oxides and silica.[19] Other particulate sources produce different mixtures of substances. On both a regional and global scale, atmospheric particulate matter plays a principal role in the transport through the air of lead, zinc, barium, vanadium, and other substances.

The chemical composition and size distribution of fine particles are important in determining the effects of this type of air pollution. For example, the health hazard associated with inhaled airborne particles depends on: 1) the site of deposition in the respiratory tract, which is determined by particle size; and 2) the effect on biological tissues at the deposition site, which depends on chemical composition. Also, the effect of particles on visibility depends on the size and refractive index of the particles, both of which are influenced by chemical composition.[18]

III

EMISSION SOURCES

Midwest Research Institute (MRI), under contract with EPA, completed a survey in 1971 of particulate emissions and control.[20,21] Some of the results are summarized in Tables 2 and 3. Nationwide, 80 percent by weight of the total particles in the atmosphere[36] are estimated to arise from natural sources.* In urban and industrial regions, man-made contributions to particulate pollution are usually many times greater than those from natural sources. The national goal of lowering urban ambient-air concentrations to 60 $\mu g/m^3$ from present levels of approximately 120 $\mu g/m^3$ will require close control over all man-made sources.

The latest detailed summary information on industrial particle emissions and properties, based on mass measurements of particles collected from stack effluents, is presented in Table 3. The MRI study[21] also provided information on particle size and chemical composition. Other measurement and rating methods for determining suspended-particle characteristics, such as light-scattering or visibility range, toxicity, and the potential of gaseous emissions to form aerosols in the atmosphere, are needed.

The objective of the MRI study was to identify, characterize, and quantify particulate emissions to the atmosphere from stationary sources in the continental United States. Emissions from each source or industry were determined from: 1) emission factors for an uncontrolled source based on a unit of production; 2) the material processed per year; 3) the average or expected efficiency of control equipment; and 4) the percentage of production capacity equipped with control devices. No new experimental measurements were made.

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*Other authors have made different estimates but all indicate that natural sources produce more emissions than do man-made sources.

TABLE 2

SOURCES OF PARTICULATE POLLUTION (WEIGHT BASIS)[21]
United States - 1968

Source	Emissions (tons)	Percent by Weight
Natural dusts	63,000,000	44.7
Forest fires	56,400,000	40.1
Subtotal		84.8
Major stationary industrial sources	18,000,000	12.9
Transportation	1,200,000	0.8
Incineration	930,000	0.7
Other Sources	1,300,000	0.8
Subtotal		15.2
TOTAL	140,800,000	100.0

TABLE 3

MAJOR STATIONARY INDUSTRIAL SOURCES OF PARTICULATES (WEIGHT BASIS)[20]
United States - 1968

Source	Efficiency of Control (%)	Application of Control (%)	Emissions (tons)
Fuel combustion			
Coal			
Electric utility			
Pulverized	92	97	2,710,000
Stoker	80	87	217,000
Cyclone	91	71	182,000
Industrial boilers			
Pulverized	85	95	322,000
Stoker	85	62	2,234,000
Cyclone	82	92	39,000
Fuel oil	--	0	134,000
Natural gas and LPG	--	0	108,000
	Total from fuel combustion		5,946,000
Crushed stone, sand, and gravel	80	25	4,600,000
Grain elevators and other agricultural operations	70	40	1,768,000
Iron and steel	90 - 99	35 - 100	1,344,000
Cement	94	94	931,000
Forest products	70 - 95	33 - 99	666,000
Lime	80 - 97	25 - 87	573,000
Clay	80	75	468,000
Primary nonferrous metals	40 - 98	35 - 100	464,000
Fertilizer and phosphate rock	80 - 97	25 - 100	337,000
Asphalt	97	99	218,000
Ferro-alloys	80 - 99	35 - 100	160,000
Iron foundries	80	25 - 33	143,000
Secondary nonferrous metals	90 - 95	20 - 95	127,000
Coal cleaning	--	100	94,000
Carbon black	--	--	93,000
Petroleum-catalyst regeneration	--	100	45,000
Acids	95 - 97	85 - 90	16,000
	Total from Other than Fuel Combustion		12,047,000
	Total Major Stationary Industrial Sources		18,000,000

The results of the MRI study[21] differ from those reported earlier by NAPCA.[4,15] This difference is probably due to the better information available for the later study. However, reported emissions may understate the true average because they are often measured only on the best of newest units operating under optimum conditions. Future research may also show that the sampling methods used were less than adequate for the task. A more detailed study to identify all sources of particulates and accumulate information on emissions is needed as a next step.

A. FUGITIVE OR OPEN SOURCES

As shown in Table 2, the largest sources of particles are natural dusts and forest fires. These are estimates based upon measurements made by researchers in the field of soil conservation and by the U.S. Forest Service.[21] These sources account for an estimated 85 percent of the national atmospheric primary-particulate loading on a mass basis and are a substantial portion of background levels. The direct effect of these particles on people, however, is much less than that of particles from man-made sources because of the concentration of the population in urban areas.

Fugitive or unconfined sources directly related to man's activities originate from agriculture, mining, construction, and transportation. A number of unconfined sources are included in the data in Table 3 (i.e., some crushing and grinding and materials-handling operations are unconfined and are important sources within a number of the processes listed).

B. CAPTIVE OR CONTAINED SOURCES

The mass (or weight) of emissions from most of the industrial sources listed in Table 3 may be highly controlled by the installation of presently available control equipment. Estimates of the mass efficiency of control equipment and the extent to which it is presently being used are given in Table 3. In some cases, such as the combustion of coal by electric utilities, over 90-percent collection efficiency is routinely achieved. Nevertheless, because of the

large amounts of coal burned, total particulate emissions from coal combustion remain a major portion of total emissions.

Not reflected in Table 3 is the relative contribution that the emissions make to the long-lived suspended-particulate levels in the atmosphere. A portion of the industrial emissions deposit near the emission point in a short time. In recognition of this, MRI also reported information on particle-size distribution, outlet particulate loadings, and chemical composition for the sources listed in Table 3.[21] Unfortunately, few data relating to size are available, and those only for a limited number of process sources.

C. SOURCES OF SECONDARY PARTICLES

Secondary particles, formed in the atmosphere from gaseous pollutants, make a significant contribution to urban air pollution.[22] For example, there are nearly equal weights of primary and secondary particulate matter from man-made sources in the Los Angeles atmosphere (Table 1). The relative proportions vary from city to city but there is little doubt that secondary-particle levels are significant in all major cities. Thus, efforts to meet the ambient-air standards for particulate matter must include control of both primary- and secondary-particle sources.

Emissions of sulfur oxides, hydrocarbons, and nitrogen oxides are given in Table 4. These gases undergo complex reactions in the atmosphere. A major portion of the gases ultimately form atmospheric aerosols and are removed by the natural cleaning processes of the atmosphere. What fraction of the gases emitted contribute to the urban atmospheric particulate problem is not known for most urban regions. However, comparison of Tables 2 and 3 with Table 4 indicates that the amount of such gaseous pollutants emitted by man's activities exceeds the amount of primary particles emitted.

TABLE 4

ESTIMATED MAJOR GASEOUS-POLLUTANT EMISSIONS[13]
United States - 1968
(10^6 Tons/Year)

Source	Sulfur Oxides*	Hydrocarbons	Nitrogen Oxides**	Carbon Monoxide
Transportation	0.8	16.6	8.1	63.8
Fuel combustion in stationary sources	24.4	0.7	10.0	1.9
Industrial sources	7.3	4.6	0.2	9.7
Solid-waste disposal	0.1	1.6	0.6	7.8
Miscellaneous	0.6	8.5	1.7	16.9
TOTAL	33.2	32.0	20.6	100.1

* SO_x expressed as SO_2.
**NO_x expressed as NO_2.

D. PROJECTIONS AND CONCLUSIONS

Forecasts of future particulate-emission levels have been made by several investigators.[20,21,24] These are based on: 1) changes in production capacity; 2) improvements in control devices; and 3) increased application of control devices based on legislative or regulatory enforcement.

If no improvement is made in the application of controls for particulate-emission sources, industrial emissions of particles may be expected to increase from the present level of 18 million tons per year to over 50 million tons per year by the year 2000. Use of the best presently available control equipment on all sources would reduce emissions to about 8 million tons per year by the year 2000. Improvements in control devices and practices might reduce emissions to as low as 2.5 million tons by the year 2000,[20] but simply reducing total mass emissions may be insufficient since emission and atmospheric formation of fine particles may continue to increase and result in more severe particulate pollution.

Control of emissions may in some instances be achieved by significant process changes that alter the quantity and character of emissions and reduce the magnitude of the control problem.[37]

There is a pressing need for detailed physical and chemical information on the nature of the particulate emissions from various sources. This should include information on particle-size distribution and or chemical composition, with special emphasis on trace metals and hazardous organic compounds. The EPA should take the lead in gathering and publishing such emission-source data.

IV

PARTICLE COLLECTION

Equipment for the control of particulate emissions from confined sources includes inertial and centrifugal collectors, low- and high-energy scrubbers, electrostatic precipitators, and cleanable fabric filters. These devices have been available for many years and are in widespread use, although, as pointed out in the previous chapter, many sources remain uncontrolled. Comprehensive reviews of the basic principles underlying the design and application of such devices, together with practical operating data, have been published elsewhere.[15,25-30]

Construction and agricultural operations rank high on the list of emission sources. Most of these operations are unconfined and result in particulate matter entering the atmosphere. Control is difficult because of the large areas encompassed by such operations and the transitory (construction) or intermittent (agriculture) nature of the activities. Equipment changes, including use of enclosed conveyors and vehicles, and improved methods of operation, such as wetting down sites and use of wind barriers, are some of the ways of reducing emissions from these open operations. *However, much more needs to be known about application of proper control methods to fugitive and unconfined sources.*

A. COLLECTION EQUIPMENT--PERFORMANCE AND COST

The estimated level of control, on a weight basis, of major sources of particulate matter for new installations is generally over 90 percent and in some cases over 99 percent. There has been a steady improvement in the collection efficiencies.

Costs of particulate-control equipment[15,21] vary widely. The costs cover a range of values because of local conditions and the nature of the particles, the gas stream, equipment size (gas volume), and design collection efficiency. Published average cost figures frequently do not reflect all cost components and fail to illustrate the great range in costs.

Some operational variables can have great effect on collector-system performance and cost. For example, the removal of sulfur oxides from effluents of coal-burning power plants through use of low-sulfur fuel can drastically lower the performance of electrostatic precipitators because this produces a more resistive fly ash and requires the use of larger and more expensive precipitators for maximum particulate-removal efficiency. An alternative method of sulfur-emission control--injection of dry limestone with the coal to remove sulfur oxides from flue gases--greatly increases the dust burden on the precipitators as well as the dust resistivity.

In the field of electrostatic-precipitator design, there is a need for more information on: 1) the influence of dust properties, such as resistivity, on its behavior in the precipitator in the presence of the electrical field; and 2) the re-entrainment effect of gas flow past the deposit.[31] This information is important because present precipitator technology is limited to a narrow band of operation in terms of collected-dust resistivity and mass-collection efficiency.

The greatest reliability problem associated with precipitators is the integrity of the charging wires. A tendency to wire failure is related to competing demands for good mechanical and electrical properties. For example, the finer the wire, the better the electrical field; however, heavier wires are required to withstand vibrations caused by electrical wind and arcing. When vibration is inhibited by fixing the top and bottom, mechanical fatigue eventually produces broken electrode wires. Several new designs use rigid electrodes in an attempt to overcome this problem.

Particle collection will, in many instances, require dealing simultaneously with collection of one or more co-contaminants. There is much interest in the use of high-energy scrubbers for the removal of sulfur oxides from flue gases. Efficient particle collection in such systems could then be achieved simultaneously with the removal of sulfur oxides. If this proves to

be practical, scrubbers may replace precipitators in some applications. The use of scrubbers has several disadvantages, such as high energy requirements, stack plumes of low buoyancy, corrosion problems, and water-disposal problems, which must be overcome. *However, combined particle and sulfur oxides control is sufficiently attractive economically to warrant support by the EPA as part of a coordinated study.* Control of particulate and gaseous pollutants cannot be considered entirely separate since both contribute to the particulate burden of the atmosphere (through gas-phase reactions).[36]

The principal limitation of fabric-filter systems is their inadequate performance when there are high temperatures in the gas stream because of the low heat tolerance of most fabrics. Although the practical upper temperature limit of fibers has been extended as new fibrous materials have become available, the maximum practical operating temperature at present is about 550° F using woven glass cloth. In the future, metal and ceramic fibrous materials may facilitate operation at temperatures up to 1000° F. Fabric-cleaning developments, such as the reverse-jet and pulsed-jet methods, have kept pace with cloth improvements. However, there is a need to develop filter housings and cleaning devices that are suitable for operation at the higher temperatures that can be reached with new fabrics.

B. THE NEED FOR SIZE-EFFICIENCY DATA FOR FINE PARTICLES

The high mass efficiencies often reported for particle collection can lead to overly optimistic conclusions about emissions because of the large tonnages involved. The small weight percentages of particles that pass through high-airflow-capacity control equipment still represent large numbers of particles escaping to the atmosphere. Moreover, collection efficiencies for the finest particles, which play a key role in air-pollution effects, are significantly less than for larger particles. For some types of collectors, such as fibrous filters, theory indicates that particle-size-removal efficiency passes through a minimum. Very small particles are removed by diffusional processes,

while large particles are captured by inertial effects. The minimum in the efficiency curve tends to occur for sizes between 0.1 and 1.0 micron, which is a particularly important range with respect to visibility, health effects, and weather modification. Some data reported for deep-bed fibrous filters indicate collection efficiencies as low as 60 percent for 0.3-micron test aerosols.[32] This is, however, not the case for fabric filters that utilize a filter cake, or dense layer of collected material, as the filter medium; these exhibit much higher retention efficiency once the cake has formed. There are too few reliable data on efficiency as a function of particle size for large operating installations to confirm the existence of a minimum based on theoretical or laboratory studies.

In the case of high-temperature particulate sources such as combustion of fossil fuel, there may be a concentration of metals such as cadmium, chromium, and lead in the smaller size fractions--possibly created by vaporization and condensation of metal fumes. Actual conditions of operation are considerably more complicated than can be accounted for in theory; hence, *there is an urgent need for reliable data on size distribution and composition of particles emitted from commercially installed and operating industrial collection equipment.*

C. THE GAS-CLEANING INDUSTRY

Present membership of the Industrial Gas Cleaning Institute consists of 29 companies in the United States and Canada. The membership includes most of the major gas-cleaning device manufacturers.

Total 1969 sales of equipment by the member companies were in excess of $100 million, not including costs of erection. In the field of particulate-emission control, it is estimated that the member companies account for over 95 percent of the dollar value of equipment sold. It is evident that the industry is of modest size. In one or two cases, consolidation has taken place among the companies, but the tendency has been for the number of manufacturers to grow. This is due in part to the anticipated market and in part to the

fact that substantial capital investment is not required for the manufacture of much of the equipment. Indeed, a large fraction of the production by some member companies is subcontracted to fabricating shops.

The Panel suggests that the gas-cleaning industry lacks a basic research commitment. The reasons are: 1) the modest value of total equipment sales divided among many competing companies; 2) the lack of specialization among the companies, many of which produce a number of different types of devices based on different physical principles; and 3) the varying requirements as to equipment performance for different applications.

D. CONCLUSIONS

Action should be taken on a national basis to develop improved capability for control of particulate emissions from both open and confined sources. This will require developing stronger research capability in the gas-cleaning industry. The Panel recommends institution of cooperative programs jointly funded by the EPA, manufacturers of industrial gas-cleaning equipment, and major equipment users.

There is a pressing need for reliable data on the size distribution and chemical composition of emissions from well-maintained, efficient gas-cleaning devices operated by industry. *The EPA should assume primary responsibility for the collection of such data, either by its own personnel or on a contractual basis.* Data obtained from such measurements would permit the enlargement of research programs for the improvement of collector efficiency. *Ideally such research should be sponsored jointly by the EPA and industry.*

The equipment manufacturers should be encouraged to assume, perhaps with support from major user groups and the federal government, primary responsibility for the improvement of the durability and reliability of control equipment. Such improvements should also strive to lower costs, improve efficiency in the small-particle range, and widen the equipment-application range. Examples of research and development

needed are: better cleaning techniques for fabric filters; improved filter-fiber characteristics and fabric life; better electrostatic precipitator components; improved precipitator reliability; better flue-gas conditioning techniques for electrostatic precipitation; improved materials of construction; improved methods for handling both wet and dry collected material; better treatment methods for liquid wastes from wet collectors to prevent water pollution; improved erosion-control techniques for inertial collectors; and improved control instrumentation.

V

SOURCE-SAMPLING AND -MEASUREMENT METHODS

A. GENERAL

Emission-source measurements are made to satisfy the following objectives: to determine compliance with a legal emission limit; to define the contribution of the source of atmospheric pollution; to determine the amount and nature of emissions for purposes of specifying control-equipment requirements; to determine the effectiveness of a control device; and to reveal the effect of a process-parameter variation. *The measurement system must be able to describe particle size, shape, concentration, composition, and light-scattering potential and the carrier-gas characteristics associated with the emission source.*

The Panel finds that major gaps exist in instrumentation for sampling and measuring the characteristics of particulate pollution; these gaps have hampered the development of rational emission and ambient-air-quality standards. Since no system is likely to be universally applicable, numerous devices designed for specific particulate compositions and conditions are needed. The Panel believes that the state of technological and scientific knowledge is sufficiently advanced for speedy major improvements in particulate-measurement instrumentation, but it is convinced that setting priorities and producing the needed hardware on planned schedules will be difficult.

Measurement of particles in process-gas streams, in stack effluents, and in the ambient atmosphere is necessary for the control of air pollution, and each location involves special requirements. Some progress has been made in the development of instruments for the measurement of particulate pollution in atmospheric air. Size spectra, total particle number, and mass can be measured on a continuous, close to real-time basis in ambient air using a variety of commercially available devices based on different physical principles:

(1) Several *optical particle counters* are marketed that, when properly calibrated and maintained, can be used to measure individual particles from 0.2-0.3 microns to about 20 microns in diameter. Efforts are currently under way to extend the counting range of such sensors below the 0.1-micron size by using conventional and laser optics. When existing sensors are combined with a multichannel analyzer, detailed size distributions can be obtained on a continuous, on-line basis.

(2) The *electrical mobility analyzer* can be used in the range below a few tenths of a micron to measure particle-size distribution with a response time of a few minutes.

(3) Particle concentrations in terms of total number can be monitored continuously using *condensation nuclei counters*, which function as automated Wilson cloud chambers operated intermittently.

(4) Particle mass can be monitored continuously using a *vibrating quartz crystal* on which the particles are deposited by electrical precipitation or impaction.

(5) Particle mass can also be monitored continuously using a *filter and associated beta gauge* with a response time for atmospheric air of about one hour.

None of the above principles has been used in a commercial instrument suitable for routine source monitoring. Also, there is no proven commercial instrument that can measure *any* of the chemical constituents of particulate pollution on a continuous, on-line basis. All the commercially available instruments or techniques in these categories are of the laboratory type and are not applicable for reliable, long-term untended field operation. Such constituents as lead, sulfate ions, and carcinogens, and many others are currently determined by collecting samples of particulate matter over periods of up to many hours and then subjecting the accumulated material to chemical analysis.

B. REQUIREMENTS FOR STACK-GAS MEASUREMENT SYSTEMS

Stack-gas sampling imposes demands on instruments that are much harsher than the requirements for measuring ambient-air quality. High temperatures, condensation, and chemically active gases, as well as complex geometric and flow configurations, complicate the problem. Requirements for stack-gas sampling include:

1. Gas-Flow Characterization

Important characteristics of the gas stream are temperature, pressure, composition, and flow uniformity. At present, the accepted method of flow measurement involves determination of velocity profile with a pitot tube and composition analysis by volume percentage of certain gases (Orsat analysis). Steady-state flow is assumed but atmospheric wind and process variability may result in large flow fluctuations across the opening of a large-diameter stack, perhaps as extreme as flow reversal in some portions of the system. Orifice, venturi, and nozzle meters are used in some instances to obtain average-flow results directly.

2. Sample Acquisition and Transport

In stack sampling, it is often necessary to remove an effluent sample from the gas stream and transport it to an analytical or collection device. The primary requirement is that the sample acquisition and transport system deliver a representative sample of particles. Thus, the sample inlet (nozzle) must not classify or fractionate the particles. This requires isokinetic sampling for particles larger than a few microns. During subsequent transport, significant deposition will occur on the walls of the sampling lines unless special design and construction of the sample line (as well as control of temperature, velocity, and partial pressure gradients in the line) are used.

3. Sample Analysis

Most accepted methods of analysis are designed to collect the total mass of the particles emitted from

a source[4] and may permit the finest particles to pass through without significant error in the mass concentration.[37] Further, the primary particles in the collector may be modified by agglomeration, dispersion, dissolution, or reaction. Usually sample analysis is carried out on collected materials. Composition analysis is made by any of the conventional wet or dry micro-chemical methods on all or part of the collected sample. Particle-size analysis is made by redispersing all or part of the collected sample and determining the number or mass in several size fractions. In a few instances, particle-size analysis is carried out by microscopic techniques. Data from two analytical methods seldom agree, not only because of non-ideal sample treatment, but also because methods in use measure different size characteristics--diameter, surface, etc. At this time, no standard procedure exists to resolve these variations in results when comparing data from different sampling methods.

4. Other Requirements

Some additional requirements or desirable features for operational particle-measurement systems to be used in source effluent streams are that they:

a. Give reproducible results;

b. Operate over the entire stack-temperature range;

c. Operate with corrosive gases and vapors;

d. Operate in flammable and/or explosive atmospheres without hazard;

e. Operate reliably during both short and long sample times (complex start-up and shutdown procedures should be avoided);

f. Operate with low power requirements and are not overly heavy;

g. Operate simply; and

h. Provide internal standardization or calibration, particularly for *in situ* instrumental analysis.

C. METHODS CURRENTLY USED

Methods of in-stack monitoring used currently incorporate the following elements:

1. A sampling nozzle, which may be an isokinetic nozzle;

2. A probe for extending the nozzle into the stack;

3. A particle collector;

4. A cooling section or condenser to remove excess moisture;

5. A gas-flow measuring device;

6. A gas pump;

7. A gas-temperature and gas-pressure measuring device; and

8. A flow-regulating device.

Table 5 summarizes the major features of several common stack-sampling trains. The differences among the systems give rise to problems in obtaining comparative results. For example, the line loss in the probes before the collector in the EPA and IIA trains will be greater than the loss in the in-stack collector used in the ASTM train. Because of condensation, the material collected in the trains where the collector is cooled may be different in composition as well as in amount from that collected in a hot collector. These effects are significant when the measurement requirements are based on mass alone. As concern with submicron particles increases, the discrepancies in measurements among the trains are likely

TABLE 5

MAJOR FEATURES OF SAMPLING TRAINS

Sampling Element	Environmental Protection Agency[7]	American Society of Mechanical Engineers PTC-27	American Society for Testing & Materials D2928-71	Incinerator Institute of America T-6
Nozzle	Gooseneck	Gooseneck or elbow	Gooseneck or elbow	Elbow
Probe	Glass-lined and heated	Stainless steel	Stainless steel	Stainless steel
Collector	Cyclone, glass fiber filter and impingers	Any at 99% efficiency for particles	Filter or thimble in stack	Cyclone and bag filter
Cooling section	Wet impingers	Condenser	Condenser	Condenser
Flow measurement and control	Pitot tube and nomograph	Totalizing gas meter	Totalizing gas meter or flowmeter	Null nozzle
Gas mover	Vane pump	Vane pump	Vane pump	Vacuum blower

to become even greater. Measurements made with the ASME and with partial and full EPA trains on high-performance fly-ash electrostatic precipitators are shown in Table 6. The two systems give significantly different particle-outlet concentrations.

Cascade impactors have been used for *in situ* size fractionation of stack samples.[33] Satisfactory size fractionation from approximately 1 micron upwards is reported, but some dispersion of large flocs occurs. The impactor can sample the stack atmosphere directly, thereby minimizing the effects of transport and storage. A sample large enough for chemical analysis may be obtained if the chemical method is sufficiently sensitive. The cascade impactor is useful for very low dust concentrations. If it is to be used for usual stack concentrations, brief sampling periods are necessary.

Radiation interference (wavelengths up to the infrared) has been used for analysis of particulate loadings in emission sources. Qualitative stack-effluent monitoring is often done visually using Ringelmann numbers or equivalent opacity and is part of many local codes and regulations. Optical methods based on light-scattering properties are used for continuous monitoring of stack gases in many industries.

D. CONCLUSIONS

Much additional research and development is required to produce measurement systems capable of giving reliable and accurate analysis of particulate effluents. Methods are needed to characterize particle-size distribution in relation to mass, aerodynamic diameter, or optical diameter. This must be done for the particles in the stack to define control-system performance and for a variety of atmospheric conditions to evaluate effects on the environment. The methods must be capable of analyzing particle sizes over a wide range, including those from 0.01 to 1 micron in diameter, and must be usable with different particle and carrier-gas compositions. *Comparative studies of in-stack sampling trains are valuable and should be continued.*

TABLE 6

HIGH-PERFORMANCE COAL FLY-ASH ELECTROSTATIC PRECIPITATOR
MEASUREMENTS WITH DIFFERENT SAMPLING TRAINS

Item	Plant	Unit	Plant A	Plant B	Plant C	Plant D
Coal	Sulfur	%	1.5	2.49	2.71	3.70
	Ash	%	15.7	13.13	10.63	17.64
	Btu/lb	(As Rec.)	11,800.0	12,566.00	10,349.00	13,837.00
	Elec. Load	MW	108.0	519.00	357.00	540.00
Precipitator	Gas flow	acfm	497,100.0	1,515,000.00	1,239,000.00	1,630,000.00
	Plate Area	ft^2	120,000.0	270,400.00	200,340.00	276,480.00
	A/V	ft^2/1000 cfm	248.0	178.00	162.00	170.00
	Temp.	F°	676.0	280.00	280.00	252.00
Performance*						
ASME Train	Efficiency	%	98.9000	--	99.3000	98.8000
	Outlet loading	gr/scf	0.0652	--	0.0263	0.0600
		lb/10^6Btu	0.1200	--	0.0597	0.1240
1/2 EPA Train**	Efficiency	%	97.0000	98.0000	98.4000	98.8000
	Outlet loading	gr/scf	0.1784	0.0828	0.0590	0.0615
		lb/10^6Btu	0.3290	0.1680	0.1330	0.1280
FULL EPA Train	Efficiency	%	96.5000	96.3000	97.1000	97.9000
	Outlet loading	gr/scf	0.2120	0.1530	0.1030	0.1025
		lb/10^6Btu	0.3900	0.3100	0.2340	0.2130

*Efficiency calculated from estimated ash carryover at 80 percent of calculated total ash.
Precipitator inlet gas loading not sampled.
**Impinger catch excluded.

Source: EPA Control Techniques Test Data

Analytical methods must be capable of describing the mass or number concentration of particles and their composition in the source effluent. Data that are integrated over a fixed gas volume or related to time variations should be obtained. *A fractionating method is required for collecting sized fractions, especially in the submicron range, for analysis of composition where composition may be a function of particle size.*

Simpler methods for measuring fine-particle concentrations and the efficiency of gas cleaners for fine particles are needed. Instruments that measure particles in stacks (at stack conditions) or at ambient conditions (outside the stack) should be developed. Unfortunately, many existing sampling trains measure the emission at some ill-defined and nonreproducible condition.

The EPA should support the development of instruments capable of continuous, on-line measurement of important chemical constituents of particulate matter. Such substances as lead and other heavy metals, sulfate and nitrate ions, and pH are of interest for public health reasons and should be accorded highest priority. Instruments capable of measurement of composition averaged over particle size will be easiest to develop. Eventually, instruments that can measure composition with respect to particle size should be developed. Because of the many possibilities for hardware development, careful attention must be given to the setting of program priorities. Planned programs for development of the most essential hardware on schedule are needed. Such plans should take cognizance of all problems, technical and economic, involved in making the equipment available to the prospective users.

VI

FINE PARTICLES

The environment in a stack or process usually differs greatly from that in the atmosphere. Stack environments are often characterized by high temperatures, high moisture content, high particle-number concentrations, the presence of co-contaminants, and a short time between particle formation and emission. Atmospheric conditions are usually characterized by low temperature, long exposure to ambient conditions, variable humidities, and particle-number concentrations so low that coagulation is negligible.

In a typical urban atmosphere most of the particles, by number, are smaller than 0.1 micron in diameter. Most of the particle surface area is in the light-scattering range from 0.1 to 1 micron in diameter and, based on the most recent studies, the mass distributions for the urban regions that have been studied show two peaks, since about half of the mass is in the 0.1- to 2-micron range while the rest is in the 2- to 30-micron range. Also, a substantial fraction of the mass of smaller particles may be liquid. The figure (p. 37) presents particulate-distribution data for Los Angeles smog. Data from Colorado and foreign areas[34] substantiate the twin-peak form of the mass and volume distribution.

A. PROPERTIES OF FINE PARTICLES

Fine particles with aerodynamic diameters smaller than 2 microns have a number of important characteristics that distinguish their behavior from that of larger particles. Fine particles compared to large particles:

1. Scatter more light per unit mass;

2. Have greater penetration through gas cleaners;

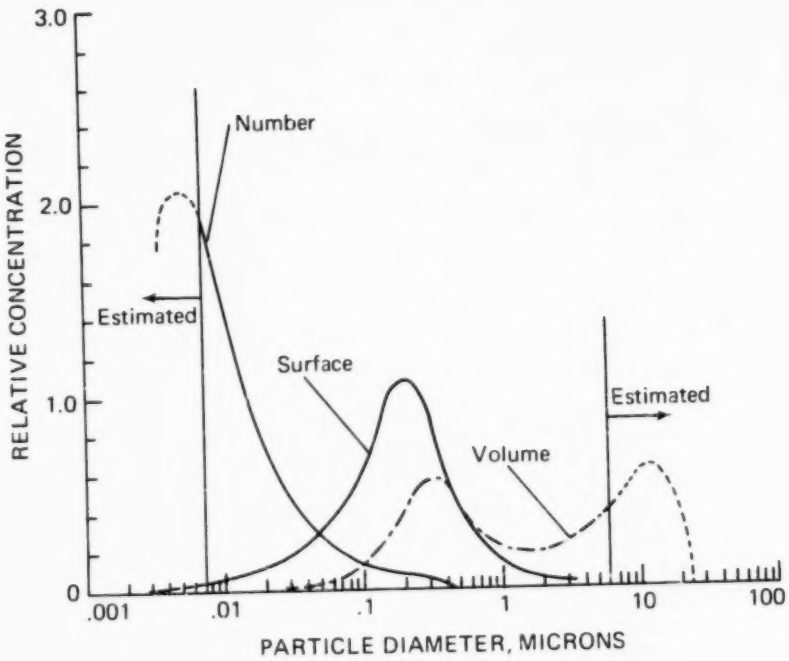

FIGURE: Typical particulate distribution

3. Penetrate more deeply into the respiratory system but may be largely exhaled over certain ranges;

4. Remain airborne in the atmosphere for longer periods;

5. Account for a greater number of particles in urban air pollution; and

6. Are usually generated by thermal or chemical processes.

B. ATMOSPHERIC PARTICLE-TRANSFORMATION PROCESSES

Fine particles typically undergo significant transformations between the time they are created and the time that they are collected in control equipment or emitted into the atmosphere. Such transformations include diffusion and coagulation, reactions with gases, growth by vapor condensation, evaporation, and adsorption or desorption of water.

Although generation mechanisms are not completely understood, it appears that most fine fumes and smoke particles resulting from flames or other high-temperature processes at the time of emission to the atmosphere consist of hundreds of thousands (10^5 to 10^6) of 0.005- to 0.05-micron-diameter primary-particle aggregates per cm^3 having a mean size of about 0.2 micron. Very small primary-particle aggregates may also grow by condensation of higher vapor-pressure liquids such as hydrocarbons and water (when they are present) during their transport in the ducts and stacks before emission to the atmosphere. Thus, at the point of emission into the atmosphere, fine particles may consist of aggregates of primary particles plus condensed vapors.

C. PRINCIPAL SOURCES OF FINE PARTICLES

1. Primary particles are produced by:

a. *Condensation.* Many chemical reactions

produce vapors at elevated temperatures. Heat loss by several mechanisms produces supersaturation, which results in nucleation of solid or liquid particles.

b. *Chemical reactions.* Particles that result from combustion, as well as noncombustion aerosols such as sulfuric acid mist, are the indirect result of chemical reactions.

c. *Comminution or powder handling.* This is a prime source of large particles, but fractures of these particles produce some fragments in the fine-particle range. Soils and sands contain fine particles that may become suspended in the atmosphere.

2. Secondary particles are those formed after leaving the stack. They can be produced by:

a. *Condensation of vapors* in the plume. The most common particles are water and hydrocarbon drops, which often form at an early stage in the plume and then evaporate as the plume mixes further with the ambient air. Exceptions are sulfuric acid mist and some chemical compounds that are sufficiently hygroscopic to hold a substantial amount of water at ambient humidities or are of low enough vapor pressure so that evaporation is very slow.

b. A variety of *reactions*, chemical and photochemical, that occur outside of the stack and result in nonvolatile products that form aerosols. Sulfate-containing particles resulting from the oxidation of SO_2 and combination with other compounds are an example. Los Angeles-type smog is also the result of photochemical reactions of emissions.[22]

c. *Evaporation* of droplets containing dissolved solids or nonvolatile liquids to form residue-solid particles. Examples are sea salt particles from bubbles bursting at the ocean surface and the residues from droplets and bubbles formed in cooling towers.

D. STATUS OF KNOWLEDGE

There are relatively few data on size distribution and concentration of fine particles from various sources. Because most sampling and evaluation in the past has been directed at measuring mass and since the fine particles usually do not contribute the majority of the mass, such measurements have not yielded good data on fine particles.[35]

Transformations of fine particles occur in stacks and in the atmosphere, but very little more is known about the transformation process of gases and particles and few studies have been made of the complete process from source to emission point and then to the atmosphere. These are difficult investigations but the results are needed to relate control techniques to effects in the atmosphere.

Because particles in stacks are exposed to conditions that are usually quite different from conditions that exist in the ambient atmosphere, measurements of fine-particle concentration and size distribution in the stack and in the atmosphere after release frequently give different results.

Most sampling methods put simplicity and low cost ahead of an ability to assess the *in situ* state of the aerosol in the stack in a satisfactory manner. The preoccupation with measurements of mass emissions and efficiency of air cleaners has severely limited measurements of the performance of gas cleaners on fine particles.

E. CONCLUSIONS

1. *More fine-particle-removal efficiency data on gas cleaners are needed.* Gas cleaners with 99 percent mass efficiency frequently have a significantly lower percent efficiency on particles below 2 microns in size. Since fine particles may have 10 or 100 times the half-life of coarser particles in the atmosphere, it is apparent that the importance of fine particles can be greater than their relative mass concentration might indicate.

2. *Techniques directed particularly toward collecting and controlling emissions of fine particles need improvement.* Improvements in collection of fine particles might be accomplished through particle-conditioning processes using electrostatic-charging, condensation, and agglomeration-promoting techniques.

3. *A strong research effort should be initiated to study ways of improving removal of fine particles and of vapors and gases that have a potential to form fine particles in the atmosphere after emission from the stack.*

4. Studies are needed to define the processes that fine particles undergo from the instant of formation until they are no longer a significant component in atmospheric processes or an air-pollution hazard.

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